The effect of tensile fatigue on chloride ion diffusion in concrete

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HIGHLIGHTS

- The role of tensile fatigue damage in concrete corrosion is experimentally studied.
- Chloride ion diffusion in concrete is characterized using multiple damage variables.
- Ion diffusion coefficient increases exponentially with damage-dependent overall resistance.
- Overall resistance is strongly correlated with residual strain and fractal damage index.
- All three damage variables provide a coherent interpretation of test results.

ARTICLE INFO

ABSTRACT

Fatigue damage is one of the most important factors impacting the chloride diffusion coefficient in concrete. In this paper, chloride ion diffusion in concrete was experimentally studied using a modified apparatus based on the rapid chloride migration (RCM) test to measure the diffusion coefficient. The effect of fatigue damage on chloride ion diffusion coefficient was analyzed using residual tensile strain, fractal damage factor (defined based on fractal dimension of damage propagation fronts) and damage-responsive variable resistance as self-variables to characterize fatigue damage. The chloride ion diffusion coefficient increases exponentially as residual tensile strain increases. An initial degradation point occurs at approximately 25 $\mu\varepsilon$. The diffusion coefficient increases exponentially with increasing fractal damage factor. The initial degradation point and steep degradation point occur at 30% and 50% fractal damage factor, respectively. An exponential increase in the ion diffusion coefficient is also observed as the damage-responsive variable resistance, ($R_{CCP} + R_{CP}$), decreases, with $3.25 \times 10^6 \, \Omega \, cm^2$ and $2.1 \times 10^6 \, \Omega \, cm^2$ being the initial degradation point and steep degradation point, respectively. The three exponential functions suggest strong correlation between the three damage variables and chloride ion diffusion coefficient.

1. Introduction

Reinforced concrete structures are currently the preferred form of civil engineering structural design. Corrosion of reinforcement is directly responsible for damages and loss of durability of concrete structures [1–3]. Chloride diffusion, i.e. the directional transport of chloride ions in a solution under chemical potential gradient, has been identified as the dominant contributor to corrosion in many applications that employ steel-reinforced concrete structures. The chloride ions do not directly participate in the corrosion reactions as they penetrate through the concrete structure, but instead perform as "catalytic porters" that destroy the passivation layer, providing current paths through the formation of corrosion cells, which greatly accelerates the corrosion process [4,5].

In addition to chloride ion attacks, stress-induced fatigue also arises in bulk concrete as it is subject to wind, wave and vehicle loads during service. Micro-structural defects induced by fatigue accumulate gradually [6,7], thereby exponentially decreasing the chloride-ingress resistance of the cover concrete [8]. Therefore, studying on effect of fatigue on chloride ion diffusion in concrete is of great significance to ensure the safe operation of concrete works in the environment of chlorine salt and to accurately predict and improve the service life of the project.

The impacts of fatigue on chloride ion ingress in concrete and the measured diffusion coefficient have been noted by several researchers. Xi et al. [9] examined the interactions between axial compression fatigue and chloride ion diffusion in three steps to determine the critical stress at which the ion diffusion rate starts to accelerate significantly as the stress grows. In a recent work conducted at Hohai University, Song et al. [10] used the electrical impedance spectra (EIS) method to analyze the damage level of

the fatigue concrete and studied the impact of compressive fatigue on chloride diffusion coefficient in ordinary Portland cement (OPC) concrete. Gontar et al. [11] applied three point loads in two fatigue control modes (i.e. load and displacement control, respectively) to study the interactions between fatigue stress and ion diffusion. Jaffer et al. [12] took an indirect approach to evaluating the impact of cyclic loads on the ingress of chloride ions through measurement of corrosion rates of reinforcing steel bars subjected to bending loads. While numerous studies have focused on the effect of compression fatigue and bending fatigue on chloride ion diffusion, little work has been done concerning the effect of tensile fatigue. In fact, most concrete damages can be classified as tensile damages. The tensile strength, therefore, controls the entire process from crack initiation, propagation to the formation of macroscopic cracks. This necessitates further investigation into the effect of tensile fatigue on chloride ion diffusion.

Traditionally, the number of fatigue cycles has been used to characterize damage. Because of the non-linear relationship between fatigue cycles and concrete damage, this method is only suitable for qualitative characterization of the effect of fatigue damage on the performance of concrete structures, but falls short of achieving an in-depth, quantitative understanding of fatigue damage. Alternative methods to characterize fatigue damage based on residual strain have not been widely applied in engineering practice. There remains a significant knowledge gap with respect to the fundamental laws governing the relationship between fatigue and chloride ion diffusion in concrete. This also calls for a new method to characterize the variation of ion diffusivity with the progress of fatigue.

In this paper, chloride ion diffusion in concrete was experimentally studied using a modified apparatus based on the rapid chloride migration (RCM) method to measure the diffusion coefficient. The residual strain method combined with fractal dimension assessment based on ultrasonic wave form analysis and electrochemical impedance spectroscopy are employed to characterize concrete damage due to tensile fatigue in order to establish the correlation between chloride diffusion and fatigue damage.

2. Experimental

2.1. Materials and concrete mixes

The tests were conducted using No. 42.5 ordinary Portland cement (Anhui Conch Cement, Ltd., China), the chemical composition of which being provided in Table 1. River sand with a fineness modulus of 2.8 was used as the fine aggregate; and crushed stone continuously graded 5–16 mm was used as the coarse aggregate. The mixing proportion of concrete is listed in Table 2.

2.2. Concrete tensile fatigue tests

The dimensions of the specimens used for the tensile fatigue test are 100 mm × 100 mm × 515 mm, each end embedded with a 16 mm dia. reinforcing bar with a penetration depth of 75 mm, and aged for 90 d under standard conditions prior to the tests. One group of test specimens was then mounted onto an MTS-810 electro-hydraulic axial fatigue testing machine equipped with a universal servo system to measure its axial tensile strength, while the other group underwent tensile fatigue tests. An additional group of standard test specimens, each sized 150 mm × 150 mm × 150 mm, was prepared and aged for 28 d for compressive strength tests.

The fatigue tests were conducted in axial tension mode, with the sides being unconstrained. The stress level applied during the tensile tests was varied from 0.50 ft, 0.60 ft, 0.70 ft to 0.75 ft. The tests pieces were subjected to 10,000, 30,000

and 50,000 load cycles, respectively, for stress levels of 0.50, 0.60 and 0.70. At a stress level of 0.75, however, each piece was subjected to 5000, 10,000 and 15,000 load cycles, respectively. The loop eigenvalue was maintained constant at 0.1. The wave form used in the tests was the conventional non-intermittent sine wave. The loading frequency was 10 Hz for stress levels of 0.50 and 0.60, and 5 Hz for stress levels of 0.70 and 0.75. Since the last two sets of specimens were tested under greater stress level, 10 Hz could cause gross damage to the specimens and render measurements difficult or impractical. The tensile fatigue test parameters are summarized in Table 3. Three specimens were tested for each case.

2.3. Tests for fatigue damage of concrete

2.3.1. Residual tensile strain

Two linear variable displacement transmitters (LVDT) were embedded between the two opposite faces of the non-pouring surface of the specimen to measure the displacement during the fatigue tests. Strain was determined from the measured displacement. The readings from two LVDT devices were averaged to obtain the mean strain.

2.3.2. Fractal dimension of concrete damage

The specimens with fatigue effect were cut into two parts to be made of specimens of 100 mm × 100 mm × 300 mm, each was polished with sandpaper. A nonmetallic ultrasonic tester was employed for ultrasonic waveform analysis, with the emitting and receiving ends being placed at symmetrical placements on both ends along the axis of the specimen. The contact surface was coated with Vaseline as a coupling agent so that the end of the specimen was in full contact with the surface. Five test points were selected on each test piece. The waveforms were obtained via a USB data acquisition interface and analyzed using a MATLAB program. The fractal dimension of the concrete damage fronts was determined by power spectrum analysis.

2.3.3. Damage-dependent overall resistance

The specimen subjected to fatigue was cut into a test piece of 100 mm × 100 mm × 100 mm. The cut surface was polished with sandpaper and pasted with copper foil tape to be used as an electrode. In order to reach a water-saturated condition, the specimens were put in a water tank for 72 h before they were taken out and sealed with epoxy resin and polythene sheets. Electrochemical impedance spectroscopy (EIS) tests were conducted with a Parstat 2273 Advanced Electrochemical Workstation. The scanning was carried out on the two-electrode cell by applying a sinusoidal potential perturbation of 5 mV at the open circuit potentials with a frequency range from 100 kHz to 10 MHz (40 points total). The EIS spectra were then analyzed with ZsimpWin software, using an equivalent-circuit model, to obtain the electrochemical parameters.

2.4. Determination of chloride ion diffusion coefficient

A modified rapid chloride migration (RCM) test was used to determine the chloride ion diffusion coefficients in concrete specimens. After the tensile fatigue tests, the specimens were cut into 100 mm cubic pieces. The cut faces were then polished. A 95 mm dia. PVC pipe was glued onto each non-section center using epoxy resin. After the epoxy resin hardened, the test piece was submerged in a water tank for 72 h before it was sealed off with epoxy resin, as shown in Fig. 1.

A fine-mesh steel wire screen, 95 mm in diameter, was placed into each of the tube bends and connected to an uninterruptible DC power supply. The voltage of the power supply was set to 30 V, with the cathode tube dipped into 0.3 mol/L NaOH aqueous solution and the anode immersed in 10 wt% NaCl solution. The initial current and cathode temperature of the test piece were recorded at the beginning of each 24-h current-on period. The final current and cathode temperature were recorded before the current was switched off. The PVC pipes were then removed and the test piece was cut into two halves along the diffusion axis. 0.1 ml/L AgNO₃ solution was sprayed onto the cut section as a colour developing reagent. The boundary of the discolored area was marked up with water-proof ink after 15 min. Since the target area for measuring the diffusion penetration depth was the 80 mm dia. core in the test piece, a 7-point averaging scheme, as illustrated in Fig. 2, was employed to obtain the mean penetration depth, based on which the diffusion coefficient was evaluated.

The chloride ion diffusion coefficient in the concrete test piece was calculated from Eq. (1):

$$D_f = \frac{0.0239 \times (273 + T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right), \tag{1}$$

Table 1
Composition of cement.

Oxides	CaO	SiO₂	Al₂O₃	Fe₂O₃	MgO	K₂O	SO₃	LOI
wt%	61.89	22.95	6.35	4.10	1.02	0.75	1.58	1.36